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**Citation for published version:**

Jin, Y, Wang, F, Carpenter, M, Weller, R, Tabor, D & Payne, S 2020, 'The effect of indoor thermal and humidity condition on the oldest-old people's comfort and skin condition in winter', *Building and Environment*, vol. 174, 106790. <https://doi.org/10.1016/j.buildenv.2020.106790>

**Digital Object Identifier (DOI):**

[10.1016/j.buildenv.2020.106790](https://doi.org/10.1016/j.buildenv.2020.106790)

**Link:**

[Link to publication record in Heriot-Watt Research Portal](#)

**Document Version:**

Peer reviewed version

**Published In:**

Building and Environment

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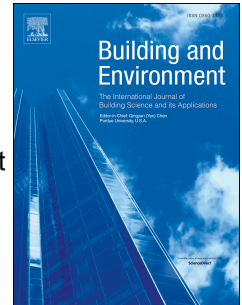
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# Journal Pre-proof

The effect of indoor thermal and humidity condition on the oldest-old people's comfort and skin condition in winter

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PII: S0360-1323(20)30148-7

DOI: <https://doi.org/10.1016/j.buildenv.2020.106790>

Reference: BAE 106790

To appear in: *Building and Environment*

Received Date: 26 November 2019

Revised Date: 22 February 2020

Accepted Date: 4 March 2020

Please cite this article as: JIN Y, Wang F, Carpenter M, Weller R, Tabor D, Payne S, The effect of indoor thermal and humidity condition on the oldest-old people's comfort and skin condition in winter *Building and Environment*, <https://doi.org/10.1016/j.buildenv.2020.106790>.

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## **The effect of indoor thermal and humidity condition on the oldest-old people's comfort and skin condition in winter**

### **Abstract:**

In winter, dry indoor air is a common phenomenon which is considered to be the cause for dry skin. A field study was carried out to investigate the thermal and humidity environment and its effect on the oldest-old people (80+ years old) residents' thermal and humidity comfort and skin condition in a Scottish care home in winter. Eleven oldest-old residents participated voluntarily in the research. The room temperature and humidity were measured together with two skin parameters: Transepidermal Water Loss (TEWL) and Stratum Corneum Hydration (SCH). The participants' personal thermal and humidity comfort was studied by a questionnaire survey and short interviews.

The monitoring results show that the average relative humidity (RH) in the bedrooms was lower than 40%, the minimum RH level in winter recommended by the CIBSE Guide A. The SCH appeared to be a good indicator for humidity comfort as it was significantly correlated with the room absolute humidity. The correlation makes it possible to predict the minimum humidity to prevent dry skin. The questionnaire results show the participants perceived a change in the room temperature but did not perceive the humidity changes. These research findings provide evidence-based data that could help to develop the indoor environment standard for these special occupants group of elderly people in care homes.

**Keywords:** oldest-old people, thermal comfort, humidity comfort, Transepidermal Water Loss, Stratum Corneum Hydration, care home

### **1. Introduction**

With ongoing advances in medical technology, care support and living style, people are generally living longer than they have in previous decades. This, however, also presents a problem: ageing of the population which is prominent in developed countries and some developing countries. In 2017, the share of the population aged 65 and over reached 19.5% while the share of the oldest-old people (80+ years old) population reached 5.5% in the EU. These proportions are still increasing in every EU country [1]. Therefore, research on the elderly population is important. Compared to other age groups, older people tend to spend most of their time indoors with more than 90% of their time spent indoors. This figure would be even higher in winter [2-4]. Since most of their time is spent indoors, the elderly people's living and well-being can greatly be affected by the quality of the indoor environment.

However, there is a lack of clear guidance for design and services provision, nor standards explicitly developed for this special group of occupants. Their physical and

mental health conditions are very different from the subjects who participated in the studies which lead to the establishment of the indoor environmental standards which guide the design and manage the indoor thermal and humidity conditions. The thermal comfort range recommended by popular HVAC design standards, such as the ASHRAE Standard 55 and CIBSE Guide A, was based on Fanger's study [5]. This involved more than 1000 young subjects and only 128 older subjects but concluded no difference in thermal comfort between younger and older people. However, the conclusion has been proved to be untenable by the fact that older people prefer a warmer environment than younger people [6] and the 20-24°C thermal comfort zone recommended by HVAC design standards is not warm enough for older people [2]. Furthermore, although few effects of low humidity were observed on thermal comfort, the prevalence of sick building syndrome (SBS) or sensation of dryness [7, 8], the minimum humidity level in winter recommended by HVAC design standards does not fit older people's health demands. For example, a minimum humidity level of 30% in winter, which is recommended by ASHRAE, is not high enough and may cause dry skin on older people [9]. Therefore, the HVAC design standards should be developed and updated for the older occupants' special demands.

Oldest-old people's living environment is often not as good as it is expected. Due to space heating and low moisture content in the outdoor air, the average RH indoors has been found to be around 30% in heated residential buildings in winter [10-12]. The dry indoor air situation is even worse in older people's living environment because of their aged physiological condition [13]. Older people are less sensitive to low humidity and normally prefer a 2°C warmer environment in winter compared to younger age groups [6, 14]. This makes the room RH lower than the typical indoor spaces and the environment drier for the older occupants. Dry indoor air has become a common wellbeing problem in older people's living environments, especially in care homes and nursing institutions for the elderly [9, 13].

Dry indoor air not only causes discomfort feelings but raises the prevalence of dry skin (xerosis) which is one of the most frequently suffered health issues among older people. It can result in a series of skin symptoms, such as itchiness, pruritus and cracks [9]. Its prevalence for older people is 29.5% to 45.3%, mostly affecting the oldest-old people amongst other age groups [9, 15]. Although the exact aetiology of dry skin on older people is not entirely understood, air humidity has been considered as an important factor in the condition's development [16]. Several studies reported that the prevalence of dry skin for older people in care homes was higher during the heating seasons and was directly associated with the dry indoor air due to space heating [17, 18]. As older people are less sensitive to low humidity and their skin condition is affected by the environment [14], the condition could indirectly reflect the effect of dry air and help them to sense the humidity. Unfortunately, very few studies can be found focusing on the effect of dry indoor air on the skin. A study, carried out in a climatic chamber comparing the data in three different RH settings (10%, 30% and 50%) for a 180-minute exposure, proposes a minimum RH of 30% to avoid dry skin on older adults [14]. Another study recommends 45% RH as the

minimum level, with no data to support the statement [9]. Thus, there is a need to investigate the impact of dry indoor air on skin condition, especially on the elderly.

The skin condition can be assessed by two dermatological variables: Transepidermal Water Loss (TEWL) and Stratum Corneum Hydration (SCH). TEWL is universally used for skin assessment as its measurement is straightforward, non-invasive and economical [19, 20]. It is defined as the flux density of water diffusing from the dermis and epidermis through the stratum corneum to the skin surface [21] and shows the capacity of the skin's barrier function, which is clinically relevant to skin diseases [19, 20, 22]. TEWL has been proved to be affected by the skin exposed environment, including the ambient air temperature, humidity and velocity [20]. This varies in different skin areas and age groups [23]. Kottner et al. [23] synthesized the TEWL of younger and older people on about 50 skin areas in 167 studies which can be used as a guideline for assessing skin condition by TEWL. According to the study, the average TEWL on the distal right volar forearm of the research subjects ageing from 18-64 years old is  $7.3\text{--}11.8\text{ g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ . An increase in the TEWL indicates an impaired skin barrier function and unhealthy skin condition [22]. Another parameter to assess the skin condition is SCH which is the moisture content in the outermost layer of skin. It is indirectly measured through a combined variable of skin's electrical properties that are relevant to the moisture content in the horny layer. When the skin is submitted to an alternating current, the total impedance of the skin can present the skin hydration status [22]. The SCH is presented in arbitrary units (a.u.). Values below 35 a.u. denote for very dry skin, between 35-50 a.u. represent dry skin and over 50 a.u. signify a sufficiently moisturized condition [24].

The aim of this study is to investigate and quantify the indoor thermal and humidity condition in a care home and explore its impact on oldest-old people's skin condition in their living environment. Through a specific survey procedure, both environmental objective data and personal subjective data are collected and analyzed. This procedure allows the data to be collected in a normal live setting that minimizes the possibility of uneasiness for the occupants taking part in the survey. Consequently, the results drawn from the data should reflect the true situations in care homes and the associated occupants' responses.

## **2. Methodology**

### **2.1 The care home**

The care home is located in the city centre of Edinburgh, Scotland, UK, where the annual heating degree days of 2850 in the past 5 years to base temperature of  $15.5^{\circ}\text{C}$ . The care home provides space heating all year round by a central heating system and offers full-time catering and residence for older females only. It is a two-story building that consists of a Georgian house to the South (including a dining room, glass conservatory, lounge, offices and maintenance rooms) and an extension to the north for 23 en-suite bedrooms. Each floor is connected by a lift and a major stair unit

in the Georgian house and a minor stair in the north extension

The living rooms, conservatory, dining room (where the occupants spent most of their time in the care home) and the participants' bedrooms were selected for data collection. Each room is heated by wall-mounted radiators with thermostatic controlling the room temperature and is ventilated by a delay-extract fan (delay off in approximately 10 minutes) in the en-suite preventing odour and moisture going into the bedroom when it is in use.

## 2.2 Research participants

Eleven participants voluntarily participated in this research through an ethically approved recruitment process. The participants are all white females, ageing from 83 to 94 (mean  $\pm$  STD: 88.81 $\pm$ 3.97) years old with no skin disease or cognitive dysfunction. Due to their very old age, they have various degrees of difficulty in hearing, reading and writing.

In the recruitment, a simple information sheet that introduces the research background, aim and objectives, was provided to all the residents in the care home. A consent form was signed and returned by eight of the participants. The rest of the participants, who have difficulty in signing their name, orally accepted the consent form and authorized their family to sign and return the consent form.

During the research, participants spent most of their time in their bedroom or in the living area and seldom left the care home due to safety reasons and the cold weather. The participants were required to stay in the places where the temperature and RH were recorded for at least one hour before our visits to ensure their body have adapted to the environment. All participants were sitting at ease (metabolic rate 60-70W/m<sup>2</sup> [25]) and were in normal winter ensemble with light outdoor clothing (clothing insulation 1.35clo to 1.55clo [25]) in our visits.

It was noted that the skin condition is affected by multiple factors, including those of health, nutrition and medical history [22, 26]. Therefore, only recruited, with the support of the manager, were the healthy occupants with no skin disease history and other medical factors were not considered due to the ethic restriction and also the scope of this study.

## 2.3 Physical measurements

The room temperature and RH were measured by the Tinytag Ultra 2 TUG-4500 Internal Temperature/Relative Humidity Data Logger. Each logger was installed at approximately 1.5m to 2.0m height in each of the measured rooms and set to log data every 10 minutes. The loggers were placed close to the chair or sofa where the occupant spends most of their time in the room. The room absolute humidity (AH) was calculated by the measured room temperature and RH. TEWL and SCH were measured on the participants' distal right volar forearm by the Courage-Khazaka

MPA-5 Central Multi-probe Unit with the Tewameter TM 300 (measuring TEWL) and the Corneometer CM 825 (measuring SCH). The skin measurements are non-invasive and did not cause any damage or discomfort to the skin. The measurement itself takes less than two minutes normally and hence causes minimal disruption to the subjects.

Device	Measurement range	Resolution	Accuracy	Uncertainty
Tinytag Ultra 2	-25 ~ 85°C	0.01°C	0.4°C	-
TUG-4500	0 ~ 95 % RH	< 0.3% RH	± 3% RH	-
Tewameter TM 300	0 ~ 70 g/h/m <sup>2</sup>	0.1 g/h/m <sup>2</sup>	-	±0.5 g/h/m <sup>2</sup>
Corneometer CM 825	-	0.1 a.u.	-	± 3%

Table 1 Specifications of the measurement devices

## 2.4 Questionnaire survey

To understand the participants' responses to the environment, a questionnaire survey was designed and carried out in parallel with the skin measurements. The questionnaire consisted of the questions on both thermal and humidity comfort. The questions on thermal comfort were based on the BS EN ISO10551-2002 [27] and ASHRAE Standard 55-2017 [25] and the questions on humidity comfort were based on relevant studies [28]. Due to the facts found in an early trial, the time to concentrate on a task for the participant group was short. The standard questionnaire (Table 2) was modified using a graphic based IOS Application on a tablet with an individual interview.

The questions consisted of subjective thermal and humidity comfort in perception, satisfaction and preference (Table 1). To assist comprehension, carefully selected images accompanied most questions: a "snowflake" presenting "cold" and a "burning sun" presenting "hot" in the thermal perception question; a "cactus in the desert" presenting "very dry" and several "water drops" presenting "very moist" in the humidity perception question; a "smiling face" presenting "comfortable" and an "angry face" presenting "extremely uncomfortable" in the thermal and humidity preference questions. A validation work was conducted to confirm that the images used were correctly associated with the thermal and humidity conditions they are designed to represent.

Each questionnaire was completed for one participant at a time in one location during one visit and all questions and answers were given orally. In addition, the questionnaire survey was associated with a short interview afterwards. The interview allowed the participants to comment on the environment in the living areas and/or in their bedrooms. Each participant could provide more than one comment.



Points	Thermal			Humidity		
	Perception	Satisfaction	Preference	Perception	Satisfaction	Preference
-3	Cold	Very Uncomfortable	Much Cooler	Very Dry	Very Uncomfortable	Much Dryer
-2	Cool	Uncomfortable	Cooler	Dry	Uncomfortable	Dryer
-1	Slightly Cool	Slightly Uncomfortable	Slightly Cooler	Slightly Dry	Slightly Uncomfortable	Slightly Dryer
0	Neutral	Comfortable	Without Change	Neutral	Comfortable	Without Change
1	Slightly Warm	-	Slightly Warmer	Slightly Moist	-	Slightly Moister
2	Warm	-	Warmer	Moist	-	Moister
3	Hot	-	Much Warmer	Humid	-	Much Moister

Table 2 Scale of subjective judgments

## 2.5 Research procedure

The research was carried out in four periods in order to cover a range of humidity levels that are likely to be found in a typical room and an intervention measure can be implemented. In the first period from January 25th to February 4th, no environmental interventions were applied to the measured bedrooms. In the second period from February 5th to February 12th, a humidity intervention was applied: all measured bedrooms were humidified by Prem-I-Air Sonico, a domestic ultrasonic air humidifier, to the target humidification setpoint of 40% RH. The humidifiers were placed close to the radiators where the upward warm air can help moisture distribution. In the third period from February 13th to February 15th, the intervention was stopped in all measured bedrooms. In the fourth period from February 16th to February 21st, the intervention was applied again in all the rooms and the target humidification was set to 50% RH. The living areas were also occupied by the occupants who did not participate in the research, therefore the intervention measure was not applied in the living rooms, dining room and conservatory during the whole research period.

Two visits were taken in each period for each participant for the skin measurements and questionnaire survey. Per visit, the skin measurements and questionnaire survey were carried out by two researchers respectively, with assistance from the care home staff. As the skin measurements would be affected by the room temperature, RH and air velocity [22], the environmental parameters were checked before the skin measurements. All the skin measurements were carried out under the condition of air velocity less than 0.05m/s.



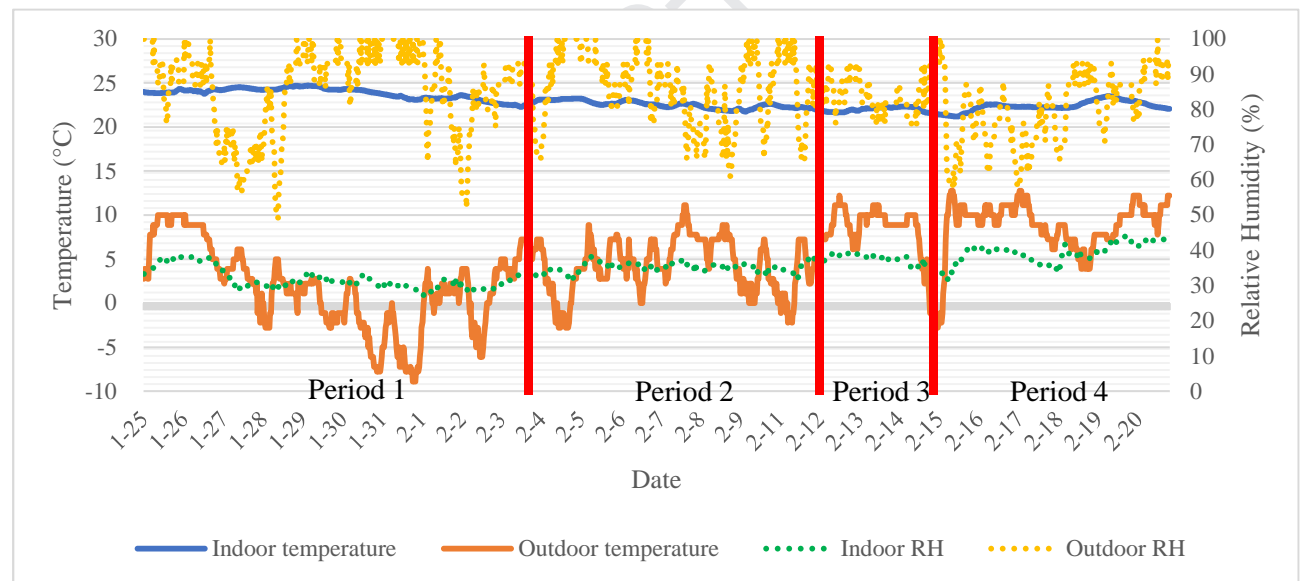
## 2.6 Statistical analysis

Data for comparing the intervened and non-intervened room condition were analyzed by the paired T-test. Results of the objective and subjective data were analyzed by repeated measure analysis of variance (ANOVA) without replication through the IBM Statistical Package for the Social Sciences (SPSS) Statistics 22 software. The significance level was set to be 0.05 ( $P < 0.05$ ). Data were expressed as means  $\pm$  SD.

## 3. Results

### 3.1 Environment measurements

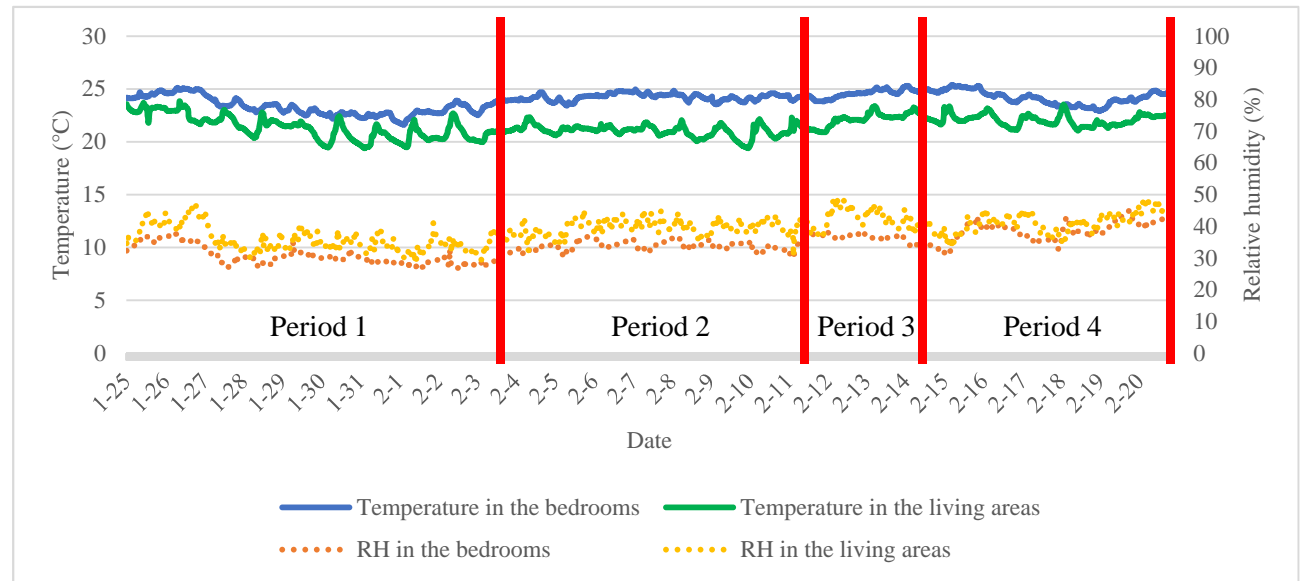
Figure 1 shows the indoor and outdoor hourly temperature and RH during the research period. The outdoor average temperature and RH were 4.8°C and 84.7%, while the indoor average temperature and RH were 22.9 °C and 35.1%. The indoor temperature and RH fluctuations were much smaller than that outdoors which shows a good performance of thermal and moisture insulation of the building.



**Figure 1 Indoor and outdoor hourly temperature and relative humidity**

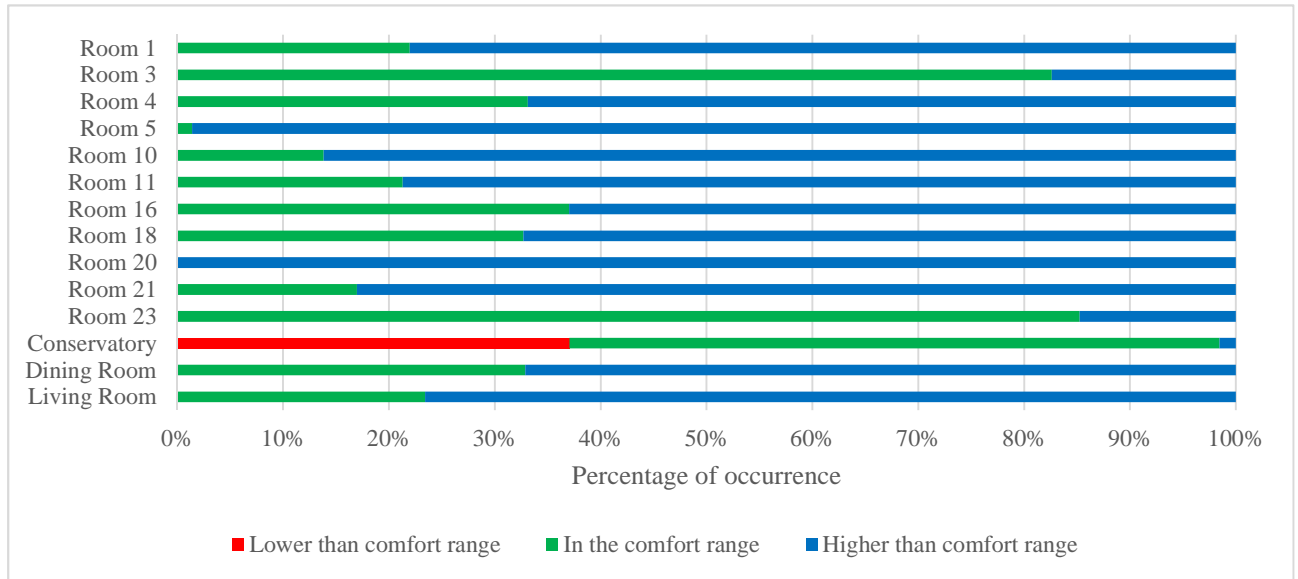
Figure 2 shows the hourly temperature and RH in the bedrooms and living areas during the research periods. The average temperature in the bedrooms and the living areas were stably kept around 23.9°C and 21.5°C respectively. The temperature in the bedrooms was normally around 2°C higher than that in the living areas. In the first period when the humidity was not intervened, the average RH in the bedrooms was 30.8%, which did not meet the minimum RH level recommended by the CIBSE standard [29]. In the second period, when the target humidification was set to 40% in the bedrooms the average room RH increased to 34.4%. In the third period when the humidification was stopped, the average room RH continuously increased to 35.6%, which did not drop as expected. In the final period when the humidification was applied again in the bedrooms and the target humidification was set to 50% RH, the

average room RH increased to 39.4%. As for the humidity in the living areas, the average RH in the conservatory was 46.5%, which was much higher than that in the dining room and living room where the average RH were 38.2% and 34.3% respectively. The higher average RH in the conservatory was very likely due to the air leakage through the window panels, which is common in glazed conservatories. In summary, humidity in the bedrooms was intervened by the humidifier but did not reach the target setpoint. Humidity in the living areas was normally about 5-10% higher than that in the bedrooms when they were not humidified.



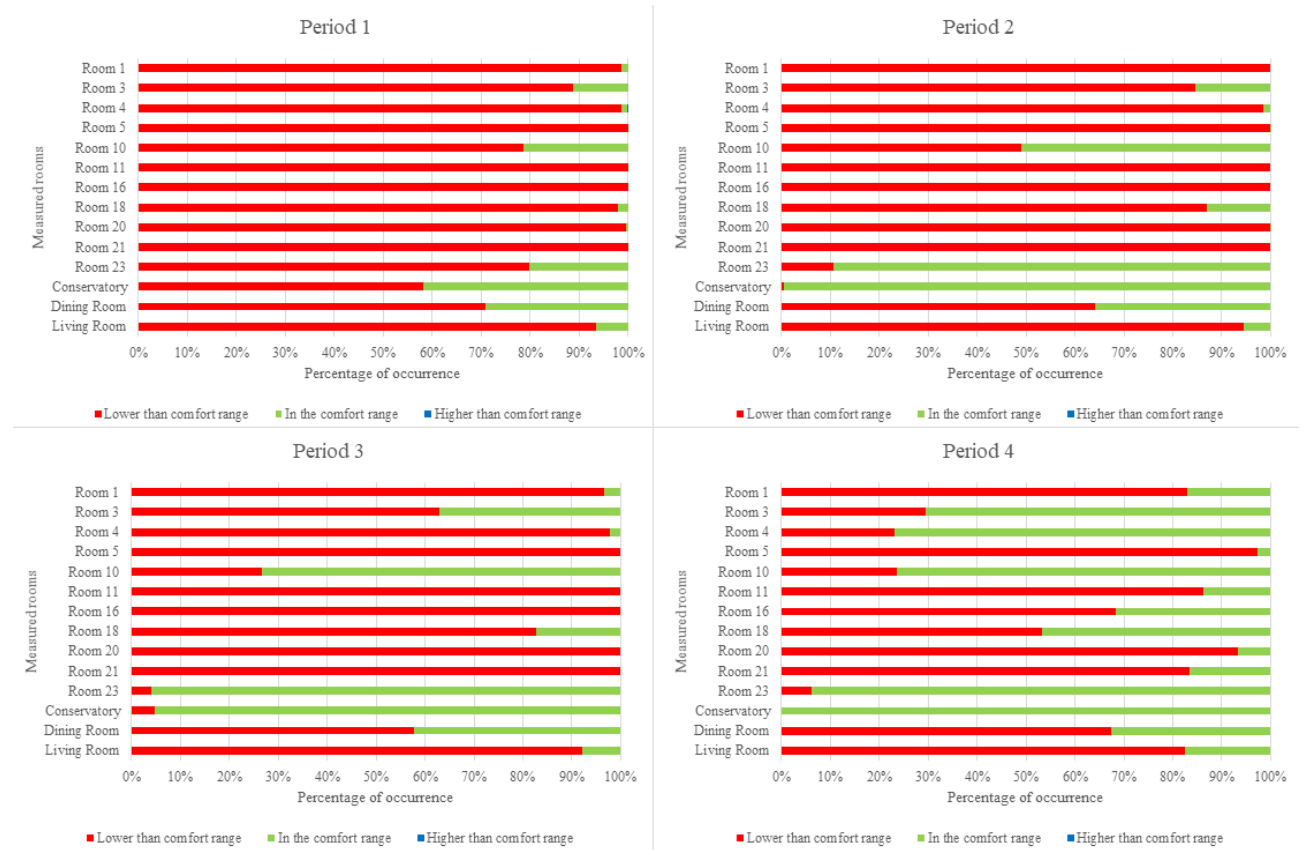
**Figure 2 Hourly temperature and RH in the bedrooms and the living areas**

Figure 3 shows the temperature distribution inside and outside the thermal comfort range for average occupants in winter (17-23°C [29]) in the measured rooms. In nine out of eleven bedrooms, the temperature was higher than the upper level of the thermal comfort range most of the time, which aligns with the fact that elderly people prefer a warmer indoor environment [2]. It is worth mentioning that room cleaning services were operated weekly in the morning. During the service, windows and doors in the bedroom were kept partly open for approximately 15-20 minutes for ventilation, which may bring down the room temperature and humidity. The temperature in the living areas was higher than the upper level of the thermal comfort range most of the time, excluding in the conservatory. The average temperature in the conservatory was 18.20°C, which is approximately 5°C lower than that in the dining room and the living room. Such a low room temperature was due to the high U-value of the glass structure in the conservatory and the high air infiltration through the glazing panels.



**Figure 3 Percentage of occurrence in and out of the thermal comfort range in each measured room (comfort range for average occupants: 17-23°C)**

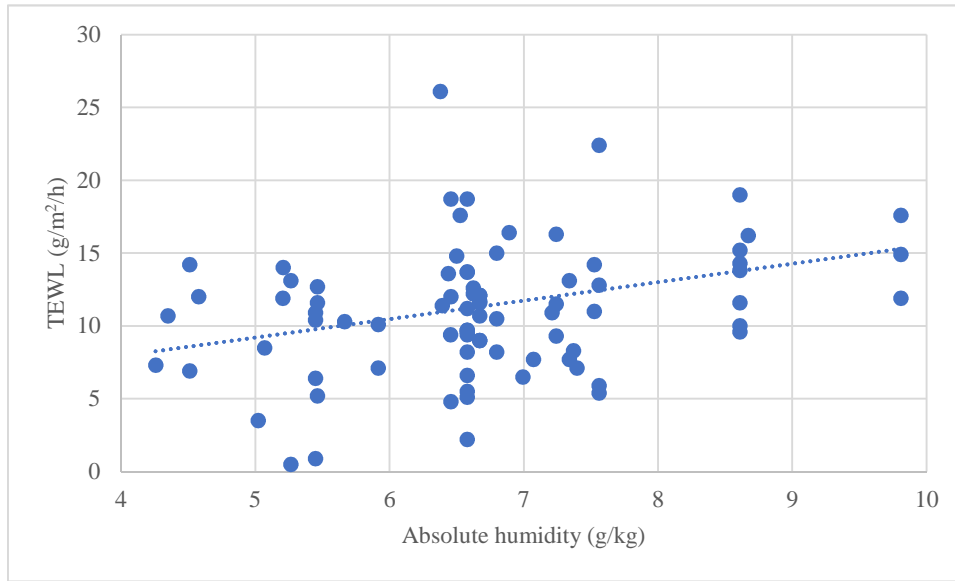
Figure 4 shows the humidity distribution in and outside of the recommended humidity comfort range (40-70% RH [29]) in all measured rooms. In the first period when no humidity intervention was applied and all the rooms were measured under their original conditions, the humidity in all the measured bedrooms was lower than the comfort range for the majority of the period. In the second period, when humidification was set to 40% RH, the humidity increased in four out of eleven bedrooms. Humidity in Room 10 and 23 was within the comfort range for more than half of the period. In the remaining nine rooms, the humidity increased by various degrees, but generally, the percentage occurrence of the humidity reaching the comfort range was not significant. In the third period when the humidity intervention stopped, the humidity in seven rooms did not drop as expected but remained more or less unchanged. This could be because ventilation in these bedrooms was not enough to remove the moisture introduced in the previous period. Moreover, in the remaining four bedrooms, the percentage of occurrence in the comfort range increased instead of decreasing or remaining unchanged. The humidity distribution in the living areas did not change significantly in the dining room and living rooms. However, humidity in the conservatory was higher than 40% since the second period but did not exceed 70% RH, the upper band of the comfort range.



**Figure 4 Percentage of occurrence in and out of the humidity comfort range in each measured room in each period (comfort range for average occupants: 40-70% RH)**

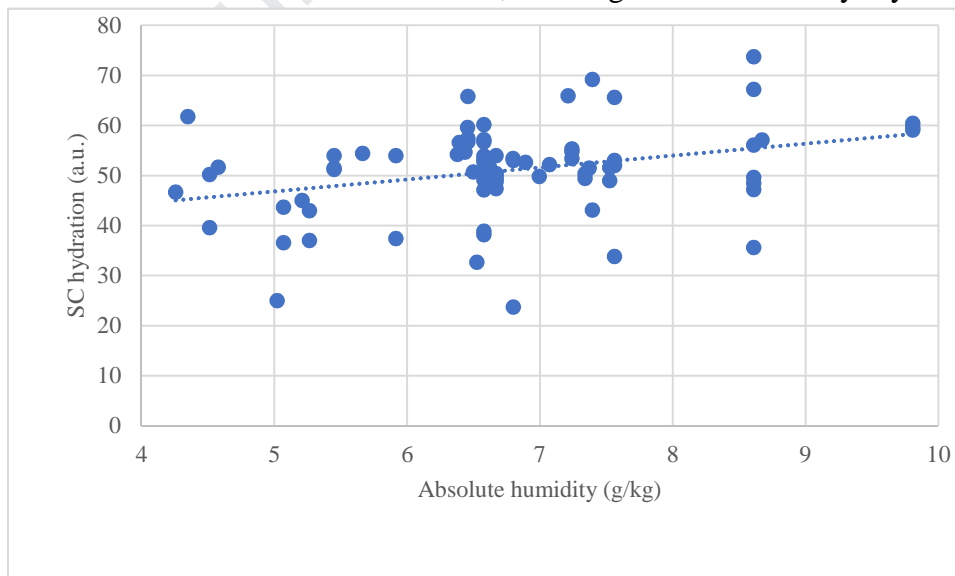
### 3.2 Skin measurements

Most of the skin measurements were carried out in the living rooms and the conservatory, in order to minimize the disruption to the participants' normal routine. The TEWL was not significantly correlated with the room temperature ( $P > 0.05$ ) but significantly correlated with the room RH ( $r = 0.32$ ,  $P < 0.01$ ). A significant correlation was also found between the TEWL and the room AH ( $r = 0.28$ ,  $P < 0.01$ , Figure 5), a variable that was derived from the room temperature and RH.



**Figure 5 TEWL as a function of the room AH at the moment of the skin measurement**

For the SCH, neither room temperature nor RH was found to be significantly correlated with the SCH ( $P > 0.05$ ). A significant correlation was found between the SCH and the room AH ( $r = 0.32$ ,  $P < 0.01$ , Figure 6). As the correlation is positive, higher room humidity contributed to a more moisturized skin condition. According to the minimum SCH of the well-moisturized skin condition (50 a.u. [24]), a minimum level of 41% RH could avoid dry skin which can be predicted if the room temperature is maintained at 21°C. In addition, 35.44% of the measured SCH levels were less than 50 a.u., showing the skin was not sufficiently hydrated. Among them, 5.1% of the measured SCH values were less than 35 a.u., showing the skin was very dry.



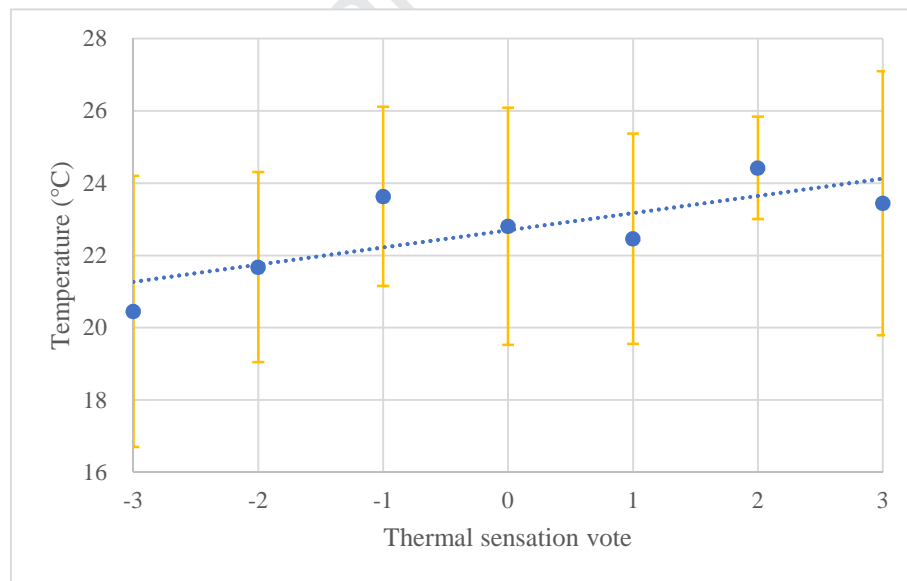
**Figure 6 SCH as a function of the room AH at the moment of the skin measurement**

### 3.3 Subjective responses

#### 3.3.1 Thermal comfort

We proposed to use the designed six-question questionnaire to investigate the participants' subjective thermal and humidity comfort in perception, satisfaction and preference. However, at the beginning of our first visit, the first two participants expressed huge impatience to the questionnaire and complained the six questions were too long. Additionally, each participant spent 15-20 minutes in answering the questions due to their difficulty in reading and hearing which was time-consuming and thus an interference to participants. Therefore, after these two participants, we used a simplified questionnaire to ask their temperature and humidity perception and a short interview to acquire their comments and complaints to the indoor environment instead of the full six-question questionnaire.

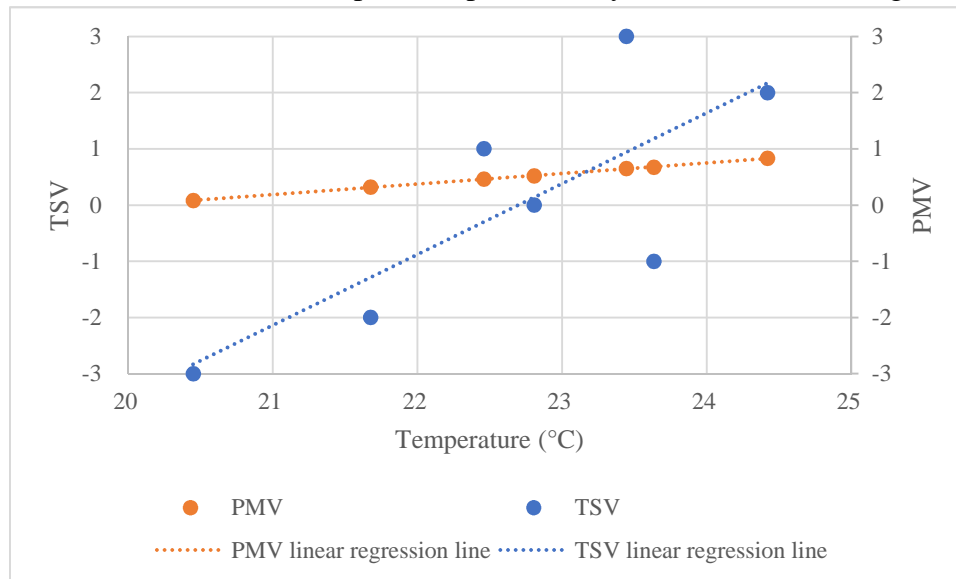
Figure 7 shows the mean temperature measured for each thermal sensation vote (TSV) and the standard deviation. The participants voted “neutral” in 51.14% of the answers. The TSV was significantly correlated with room temperature ( $r=0.77$ ,  $P<0.05$ ). As the correlation was positive, the participants' thermal perception increased with the room temperature, which shows the participants could sense the temperature change and express their perception. According to the linear regression line, a neutral temperature of 22.7°C can be predicted.



**Figure 7 Relationship between thermal sensation vote and the measured temperature**

Figure 8 compares the TSV and the predictive mean vote (PMV) at different temperature. Each PMV point is positive which means predicts the participants should sense thermally neutral or warm in the recorded temperature range. However, the prediction differs from the TSV which shows the participants felt at least “slightly cool” when the temperature was below 22.8°C. Moreover, a significant correlation is

observed between the PMV and temperature ( $r=0.99$ ,  $P<0.001$ ). According to its linear regression line, a neutral temperature of  $20.0^{\circ}\text{C}$  can be predicted, which is  $2.7^{\circ}\text{C}$  lower than the neutral temperature predicted by the TSV method (Figure 7).

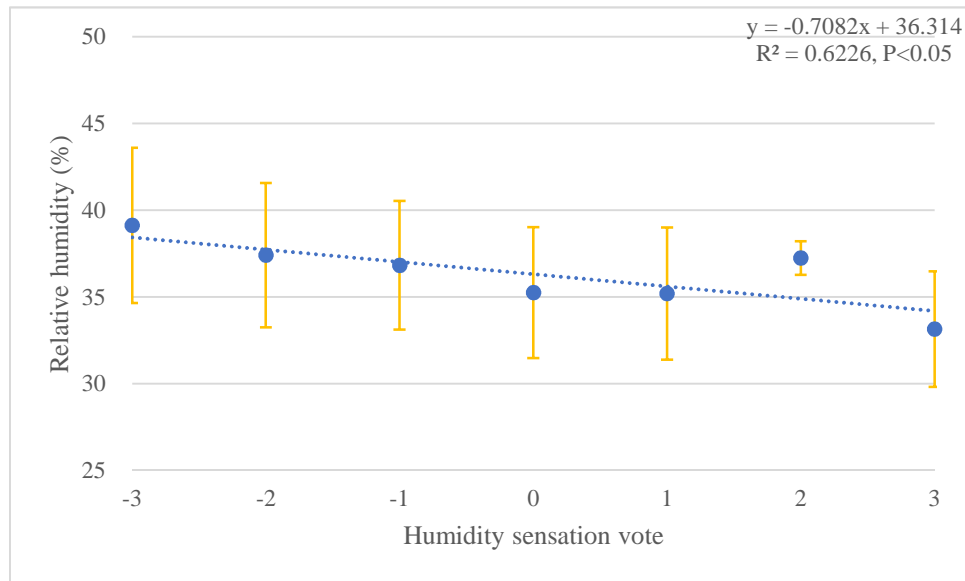


**Figure 8 Linear relationship between TSV and PMV at the average temperature recorded for each thermal sensation vote**

### 3.3.2 Humidity comfort

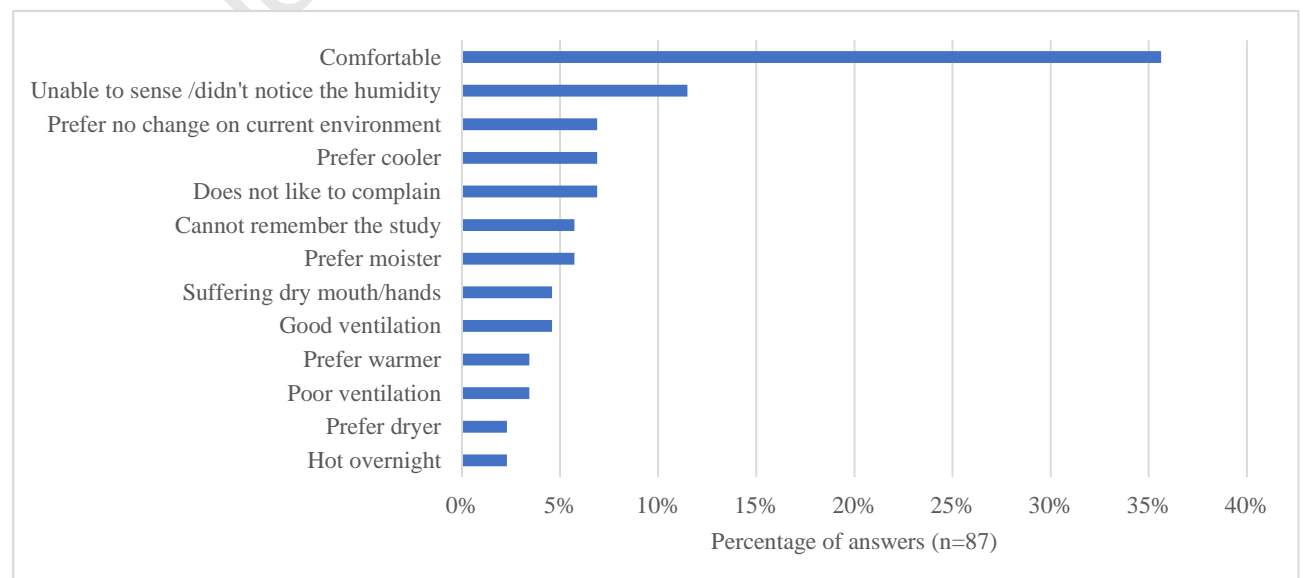
Figure 9 shows the mean RH measured for each humidity sensation vote and the standard deviation. The participants' humidity sensation was significantly negatively correlated with room RH ( $r=-0.79$ ,  $P<0.05$ ), which means the participants felt even dryer when room humidity increased. In addition, no significant correlation was found between humidity perception and room AH ( $P>0.05$ ). This may be because the participants were not able to sense the humidity change and/or the room RH was not the major factor affecting their humidity sensation. Many early studies have well established the fact that human beings are much less sensitive to the change of the humidity than the temperature in their normal range of comfort [30]. This could explain the difficulty in judging the humidity comfort with the small change of the room humidity, especially within a normal range of 30%-50% RH.





**Figure 9 Relationship between humidity sensation vote and the measured RH**  
**3.3.3 participants' comments and complaints**

87 comments or complaints on the indoor environment were obtained from the 73 interviews after the questionnaire survey (Figure 10). In 26 interviews, the participants unequivocally expressed "comfortable" with the environment. However, because all the interviews were carried out under the supervision of the care home staff, some participants may not wish to complain in their presence and always expressed "comfortable" in the interview. In addition to this, in six interviews, the participants expressed they did not like to complain, which may also be because of the presence of the care home staff. Moreover, in ten interviews, the participants unequivocally expressed they were unable to sense or did not notice the humidity in the room.



**Figure 10 Comments and complaints on the indoor environment**

## 4. Discussion

### 4.1 Indoor environment and comfort

In this study, the measured temperature in bedrooms was higher than the thermal comfort range but most of the older participants were satisfied with the temperature, which shows the older participants preferred a warmer environment and the thermal comfort range recommended by HVAC design standards is not warm enough for them. This phenomenon has been reported and discussed by van Hoof [2], who pointed out weakness of the thermal comfort range recommended by the popular HVAC design standards, such as ASHRAE Standard 55 and CIBSE Guide A. Their recommended thermal comfort range was based on Fanger's studies [5], who concluded no difference in thermal preference was assumed between younger and older people through climate chamber studies involving approximately 1300 college-age students and much smaller sample size of 128 older subjects. However, studies within the past decades show the assumption is untenable. Several studies show that older adults were thermally neutral at 23°C in contrast to 21°C for young adults, showing that older adults physiologically prefer a 2°C warmer environment than younger adults and the recommended thermal comfort range is not warm enough for older adults [6, 31]. The same phenomenon was observed in our study that the neutral temperature predicted by the TSV method is 2.7°C higher than that predicted by the PMV method (Figure 8). Therefore, the current thermal comfort range is not warm enough for older occupants and should be updated to fit their needs.

Humidity in the bedrooms was constantly lower than the recommended level when no humidity intervention was applied and should be increased at least closer to the lower end of the recommended range. The average RH in the bedrooms in this period was 30.8%, which was much lower than 40% RH, the recommended minimum RH in winter [29]. Unlike the temperature, indoor humidity is mainly affected by the occupant's activities such as washing amongst others, making it possible for the occupants to adjust the indoor humidity by adapting behaviours. For example, drying a wet towel or spraying water in normal circumstances, however, due to the participants' very old age and safety considerations, they are typically unable to actively adjust but passively bear the environment. To help ease the problem, using a humidifier could be a simple and effective solution. As shown in Figure 4, the percentage of time when the humidity is in the comfort range significantly improved when the humidifiers were used. However, the use of humidifiers is not common in winter. Research on the frequency of humidifier usage in South Korea shows that only 37.2% of the interviewed people used humidifier from December to February, and this figure dropped to 3.2% in the age group over 60 years old [32]. Therefore, promoting the using of humidifiers can effectively improve the humidity comfort in winter heated care homes, especially in the bedrooms.

Moreover, poor ventilation is another issue in the bedrooms in the care home. In this research, room humidity could be seen as an indicator of ventilation efficiency. In the

third period when the humidification stopped, the RH in most of the bedrooms did not decrease as it was expected to (Figure 4), which means the ventilation in the bedrooms was not sufficient to exhaust the moisture generated in the previous period. If the moisture generated cannot be exhausted and the humidification continues without control, the accumulated moisture could result in high room humidity and increase the emission of VOCs (volatile organic compounds). Researches show that increasing RH could considerably contribute to the emission of VOCs from building materials [33, 34] and the VOCs could create health problems[35]. Thus, the humidification process in residential buildings should accompany with sufficient ventilation.

## 4.2 Skin condition measurements

The measured TEWL was significantly positively correlated with the room RH ( $r=0.32$ ,  $P<0.01$ ) and the room AH ( $r=0.28$ ,  $P<0.01$ ) respectively, which means higher room humidity leads to a higher TEWL. However, as a higher TEWL indicates a poorer skin barrier function, this result is opposite to a validated conclusion that higher skin exposed humidity contributes to a better skin condition and could ease the dry skin [9, 16, 22]. One possible explanation to the result is both the skin's TEWL and the measurement accuracy were affected when the room environmental condition changed. The TEWL is recommended to be measured at a constant room condition with temperature 18-21°C and RH of 40-60% [20]. However, such a recommended condition was not met in this study and the TEWL measurements were carried out at different room temperature and RH. In addition to this, the measurement device is likely to be affected by the environment. The measurement device Tewameter TM 300 uses an open-chamber method whose measurement sensors are exposed to the ambient environment, making it very likely to be affected by the ambient temperature and humidity change and air movement. One study that was carried out in an inconstant environment also reports an increase of TEWL when skin exposed RH increased from 10% to 50% [14]. Therefore, measuring the TEWL in an inconstant environment is infeasible and the measured TEWL in this study is not suitable for reflecting the effect of indoor humidity on skin condition.

For the measured SCH, it was not significantly correlated with either the room temperature or the RH ( $P>0.05$ ). This result is different from the climatic chamber studies that reported the SCH shows a steady increase in function of the temperature above 22°C at constant humidity [36] and follows a linear relation ( $r=0.98$ ) in function of an increase in RH from 37% to 87% at constant temperature of 18-22°C [37]. However, a significant correlation was found between the SCH and AH ( $r=0.32$ ,  $P<0.01$ ). The weak but significant correlation between AH and stratum corneum hydration is just what we would expect in a multifactorial system. This result shows the room humidity affected the skin hydration more than the room temperature did and, more importantly, this effect is measurable at varied temperature and humidity levels in a real living environment. The stratum corneum is the major component of

the epidermis which is directly exposed to the ambient environment. Low humidity in the ambient environment may result in a decrease of the hydration state in the stratum corneum, which may attribute to changes in the keratinization process. This is a balance between keratinocytes' flattening after they migrate from the basal layer to the stratum corneum and desquamating when the cells die off. Any imbalance in the keratinization process will result in flaking and dry skin [9]. By measuring the SCH at different room humidity levels, a numerical relationship between the room thermal and humidity condition and skin condition can be established and the minimum humidity level that could prevent dry skin can be predicted. In this research, a minimum level of 40.6% that could make the skin in a well-hydrated condition can be predicted if the room temperature is maintained at 21°C. This method is applicative to not only oldest-old people but also all other age groups, especially those who are not able to participate in climatic chamber studies, to solve the dry skin issue in winter.

### 4.3 The questionnaire survey

We also noticed that the seven-scale and the questions in the standard CIBSE questionnaire were not appropriate to be used for the oldest-old special subjects in this study. Firstly, the seven-scale provided too many options as almost all of the subjects found it was difficult to differentiate between two neighbouring scales. Hence a simpler way should be applied. The scale of five, or even three could be enough for this group of subjects. Secondly, the questions were too long for the oldest-old participants, who had difficulty in reading, hearing and writing due to their very old age, and therefore trying to understand and answer may cause them stress. To solve this problem, the questions were displayed by a tablet as well as asked verbally and a short interview was arranged with each subject to acquire their subjective responses, comments and complaints. By doing this, the participants were more willing to communicate with us and provided more information in a pleasant way. Thirdly, the participants often gave irrelevant answers to our questions. For example, when we were answering "how do you feel about the temperature at this moment?" and presented the seven-point answers on the scale from "cold" to "hot", most of them would answer "I feel comfortable" or "I am fine". To solve this problem, some images, for example using smiling and angry faces to present satisfaction and dissatisfaction, were selected to help them give the relevant answer and make the communication efficient. Finally, the presence of the care home staff may interfere with the results of the questionnaire survey. Due to the ethical and safety considerations, this study was carried out with the assistance and under the supervision of the care home staff. Sometimes the care home staff would help us to ask the questions to the participants. However, some participants seemed unwilling to complain and more selective to the "comfortable" and "neutral" answers in front of the care home staffs, although they had been informed the questionnaire survey was the part of academic research and their answers would not give any negative impact on the care home or themselves. Because of this, we communicated with some participants in private, but they all denied that they refused to tell true feelings because of the presence of the care home staffs. These findings could help and give innovations to research concerning

oldest-old people.

#### **4.4 Research limitation**

Due to the availability of care home, the research participants were all females and therefore gender difference is not considered in the research. However, studies show that the thermal preference of older people in males and females are different. A study in the UK reported that older females felt warmer than younger adults at the same room temperature but no age-dependent difference was found among males [38]. Another study investigated 61 females and 59 males aged from 14 to 80 in Harbin, China and reported the neutral operative temperature for females is 1°C higher than that for males and females were more sensitive to temperature changes, although the females had a higher clothing level than males [39]. Therefore, the gender difference is a factor should be considered but ignored in our study due to the availability of the research site.

It was noted that the sample size was not large enough to allow us to derive a generic conclusion. This is because no previous similar studies could be found to estimate the sample sizes that allow us to obtain significant results and this study pragmatically recruited as many patients as could be found. The findings of a significant correlation between AH and SCH suggest that our sample size was large enough.

#### **5. Conclusion**

Overall, the subjective assessment using questionnaire surveys shows that the participants were generally satisfied with the thermal and humidity condition in the care home. However, the thermal neutral temperature predicted by the PMV method is 2.7°C lower than that predicted by the TSV method, indicating thermal comfort range recommended by the popular HVAC design standards should be updated to fit older people's needs. Besides, the objective measurement shows that the humidity in the bedrooms was low and did not meet the HVAC design criteria. By using a humidifier, the room humidity could significantly improve the room humidity, but sufficient ventilation should be provided to prevent over humidification and the extra VOCs emitted due to high humidity.

The TEWL is not suitable for measuring the effect of indoor humidity on the skin condition in the real living environment due to the inconstant measurement environment and the uncertainty of the measurement method and device used in this study. The SCH showed a significant correlation with the room AH. Based on its correlation with the room AH, a minimum humidity of 41% RH that could avoid dry skin which can be predicted if the room temperature is maintained at 21°C. By measuring the SCH in various humidity levels, the relationship between indoor environment and skin hydration can be established, making it possible to predict the minimum humidity level that could avoid dry skin in winter.

The traditional seven scales in the thermal and humidity comfort questionnaire were too many when applying to oldest-old people because of difficulty to distinguish the subtle difference between any two neighbouring scales. As they also have difficulty in reading and writing, the questionnaire survey should be conducted by one to one communication, which demands extra time, patience and cooperation from the participants. To address this issue, the future questionnaire surveys on the older people should have a revised short version and be associated with a short interview to allow the interviewees complaining or commenting on the environment instead of just answering questions. In addition, using appropriate graphics could aid oldest-old people in understanding the questions. Moreover, as the research was carried out under the supervision of the care home staffs due to ethical and safety considerations, the presence of the staff may have affected the participants' feedback. Measures should be considered to avoid the interference on the participants' answers from the irrelevant personnel in future studies.

Finally, the study was the first stage of the attempt to collect evidence-based data that would show a feasible way to develop an appropriate thermal and humidity range for older occupants' comfort and skin health. The study should be continued to cover more subjects and gather more data to build better confidence, and eventually lead to the establishment of specific standards of this very special group of elderly occupants. By doing so, it can guide the design and service providers to offer better comfort and wellbeing for the final stage of their lives in care homes.

### **Acknowledgements**

The authors would like to thank Mrs Alison Scobie and the care home staffs for their support and help in the study. Grateful acknowledgements to the eleven research participants and the other residents in the care home for their cooperation and patience. This work is a part of a PhD study funded by Heriot-Watt University.

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**Highlights:**

- A special subject group: the oldest-old (80+ years old) residents of a care home
- A field study in the real living environment – care home with multidisciplinary views from the building physics, environmental psychology and dermatology
- The oldest-old people are not sensitive to humidity change in the range of 25-50%
- Stratum Corneum hydration increases with the room absolute humidity
- A minimum humidity level required to alleviate the discomfort of dry skin can be determined by measuring Stratum Corneum hydration

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22<sup>nd</sup> Feb 2020

Dear Editor,

I, Fan Wang, on behalf of the authors listed below, declare that we are allowed to publish the findings from this study, and we have obtained permissions from our research partners, which complies with the Ethical regulation of Heriot-Watt University. We will also acknowledge the supports from sponsors for a PhD studentship for one of the authors and access to the care home for the survey.

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